Dames & Moore Model for Liquefaction Analysis
3D CPP UDM Model - Development Draft

Model Overview

The Dames & Moore liquefaction model is a Mohr-Coulomb (linear elastic/perfectly plastic) soil model coupled with an empirical pore pressure generation scheme. Pore pressure is generated in response to shear stress cycles, following the cyclic-stress approach of Seed (Seed et al., 1976; Seed, 1979). However, unlike the standard cyclic stress approach where liquefaction potential is assessed as a post-processing step, pore-pressure generation is fully integrated with the dynamic analysis.

Pore pressures are continuously updated for each element in response to shear stress cycles. Effective stresses decrease with increasing pore pressure, and a state of liquefaction is approached for frictional materials. As the available shear strength decreases, increments of permanent deformation are accumulated. In addition, the plastic strains generated as a result of increased pore pressures significantly contribute to the internal damping of the modeled earth structure. The simultaneous coupling of pore pressure generation with the stress analysis results in a more realistic dynamic response of the model.

The pore-pressure generation scheme is illustrated schematically in Figure 1. The shear stress time history of each element is monitored and shear stress cycles are counted. As soon as a stress cycle is detected the excess pore pressure is incremented by an amount dependent on the cyclic stress ratio of that cycle.

In practice it is easier to count half cycles rather than full cycles, which are detected by looking for shear stress reversals. The increment of excess pore pressure due to each stress cycle detected is computed from the cyclic strength curve. The effect of increasing the pore pressure is to decrease the effective stress and, thus, to decrease the shear strength. The elastic shear modulus is also reduced as effective stress decreases.

The Simplified Procedure contains correction factors for adjusting the cyclic strength for initial vertical effective stress greater than 1 atmosphere (K_σ) and for initial static shear stress (K_α). Both factors are included in the model following the latest recommendations of the 1996 NCEER and 1998 NCEER/NSF workshops (Youd & Idriss, 2001).

The model incorporates post-liquefaction residual strength by using a two-segment failure envelope consisting of an initial residual-cohesion value and zero friction angle which is extended to intersect with the actual Mohr-Coulomb failure envelope (Figure 2). Residual strength can be estimated from standard penetration test (SPT) blow counts using the empirical chart of Seed and Harder (1990) or using the residual-strength ratio approach of Stark and Mesri (1992).

This framework, based on the Mohr-Coulomb soil model coupled with incremental pore pressure generation, has been employed on various projects involving dynamic deformation analysis of dams (Roth et al., 1991; Roth et al., 1993; Dawson et al, 2001), analysis of dynamic soil-structure interaction of wharf structures (Roth et al., 1992), and prediction of dynamic centrifuge tests (Inel et al., 1993; Roth and Inel, 1993).

Technical Details

The excess pore pressure generated by the model is described in terms of the pore pressure ratio r_u

$$r_u = {u_e}/{\sigma'_{v0}}$$

where u_e is the excess pore pressure (generated during shaking). The model tracks and detects cycles of the stress ratio, defined as the shear stress acting on horizontal planes divided by the initial static vertical effective stress.

$$\tau_{ratio} = {\sigma_{xy}}/{\sigma'_{v0}}$$

When a cycle in the stress ratio is detected, this magnitude, or cyclic stress ratio of the cycle is designated CSR_i and the number of uniform cycles N_i for liquefaction at this cyclic stress ratio is computed from a cyclic strength curve of the form

$$N_i = 15\left(\frac{CSR_{15}}{CSR_i}\right)^B \qquad 1 \le N_i \le 100$$

Where CSR_{15} and the constant B are input parameters. CSR_{15} is the cyclic stress ratio required for liquefaction in 15 cycles (corresponding to an earthquake magnitude of 7.5) while B is a constant controlling the overall slope of the cyclic strength curve. B defaults to 2.97, which matches the empirical SPT-based liquefaction correlations and magnitude scaling factors recommended by Idriss-Boulanger (2003). Typical cyclic strength curves are shown in Figure 3.

The cyclic strength curve defines the material behavior for an effective vertical stress of one atmosphere and with zero static shear stress acting on horizontal planes (level ground conditions). The Simplified Procedure includes a correction factor K_σ for adjusting the cyclic strength for initial vertical effective stress greater than 1 atmosphere and another correction factor K_α to account for a non-zero initial static shear stress. The K_σ factor is included in the model following the recommendations of the 1996 NCEER and 1998 NCEER/NSF workshops (Youd & Idriss, 2001) using the relation

$$K_\sigma = \left(\sigma_v' / P_{atm} \right)^{(f-1)}$$

where P_{atm} is atmospheric pressure. The parameter f is a function of the relative density D_r of the soil. Suggested values for f are:

D_r	f
40% - 60%	0.7 to 0.8
60% - 80%	0.6 to 0.7

Note the relative density D_r can be estimated from normalized clean sand SPT blow count by

$$D_r = \sqrt{(N_1)_{60} / 46}$$

The K_α correction factor is computed following the recommendations of Idriss and Boulanger (2003), using the relative state parameter which is a function of overburden stress and SPT blow count. Note that these K_α corrections can be quite significant, especially for denser materials, as shown in Figure 4.

Post-Liquefaction Residual Strength

Post-liquefaction residual strength can be specified as a either an undrained strength or as a ratio of initial vertical effective stress. If an undrained strength is specified, this strength is limited, on an element by element basis, to the initial drained strength of the element.

Effective-stress dependent shear modulus

During cyclic loading, the elastic shear modulus is reduced as pore pressure increases using the formula:

$$G = G_{initial}\sqrt{1 - r_u}$$

where r_u is the pore pressure ratio as defined above. The initial shear modulus $G_{initial}$ is stored during model initialization. The shear modulus obviously cannot be reduce all the way to zero, so the model includes an input parameter specifying the minimum allowable shear modulus for the element. This parameter defaults to 1 atmosphere.

Bulk Modulus of Water

Since the model does not generate pore pressure through volumetric strains of the soil skeleton, the bulk modulus assigned to water should not have a great effect on analysis results. Thus, there is on need to use a realistic bulk modulus for water. However, an extremely low bulk modulus for water has been found to cause problems for large strain simulations where significant slumping occurs. In these cases, slumping can lead to pore pressures in slope surface elements which are too high for the hydrostatic boundary pressures applied, leading to runaway tensile failure at the slope surface. This behavior can be prevented with a higher water bulk modulus, as pore pressure is immediately reduced by the volumetric strain induced by the tensile failure.

Cycle Counting

Cycle counting, especially in real-time, is a somewhat arbitrary procedure. Depending on how the counting is done, an irregular time history can be counted as many small cycles or a few big cycles. The model ignores very small cycles (noise) by using a threshold cycle level which can be modified by the user. This parameter defaults to a cyclic stress ratio of 0.03, which seems to work well for typical California earthquake modeling where the peak ground acceleration is usually in the range of 0.1 to 1.0+. This default value might have to be decreases for very low shaking levels or increased for very noisy simulations. Note that the model counts stress cycles, and fortunately stress time histories are much less noisy than acceleration time histories.

The model includes several variables for monitoring the cycle counting process, and these should be checked for at least a few elements in any simulation to verify that the cycle counting if reasonable.

Key Input Parameters

Key input parameters for the Dames & Moore model are described in this section. These are the parameters which must be specified for a typical analysis. The model has many other input parameters, but those default to reasonable values and do not necessarily need to be changed.

General Flags and Switches

Input Property	Description
dm_mode	Switch controlling which of three modes the model run in. In mode 0, the model behaves like built-in Mohr-Coulomb model. In mode 1, the model initializes. In model 2, the model generates pore pressure.
dry_zone	Flag for unsaturated zones (above water table). Model skips pore pressure generation for zones with sd_dry_zone = 1.

Mohr-Coulomb Properties

The basic elasto-plastic behavior of the model is specified with the usual Mohr-Coulomb parameters through the variables

Input Property	Description

shear	Elastic shear modulus
bulk	Elastic bulk modulus
friction	Friction angle (in degrees)
tension	Tensile strength
dilation	Dilation angle (should be zero during pore pressure generation)
cohesion	Generally zero for sands, but can be used for modeling silts, etc

Cyclic Strength

Liquefaction resistance is input in terms of a cyclic strength curve of the form shown in Figure 3. The key input parameters are:

Input Property	Description
crr_15	cyclic stress ratio which causes liquefaction in 15 cycles
crr_exponent	Exponent defining shape of cyclic strength curve. Defaults to 2.97 which corresponds to empirical SPT-based curves based on Idriss & Boulanger scaling factors

Cyclic Strength Correction Factors

The correction factor for initial vertical effective stress greater than 1 atmosphere is computed using the formula:

Input Property	Description
dm_patm	Atmospheric pressure. Defaults to 101e3.
sigma_f	Parameter f used in the Youd & Idriss formula for the correction K_σ factor. f is a function of relative density as described above.
n160_k_alpha	Clean sand normalized blow count used in Idriss and Boulanger formulas for K_α correction factor

Post-Liquefaction Residual Strength

Post liquefaction residual strength can be specified as an undrained strength following the approach of Seed and Harder (1990), or as a fraction of initial vertical effective stress following the approach of Stark and Mesri (1992). Input parameters are:

Input Property	Description
resid_strength	Undrained shear strength for Seed & Harder approach
resid_ratio	Ratio of post-liquefaction residual shear strength to initial vertical effective stress for Stark & Mesri / Olsen & Stark approach

For the Seed & Harder approach, the post liquefaction residual strength is specified with the variable sd_residual_strength. However, during initialization mode (described later) this strength is limited to the static drained strength of the material.

For the Olsen & Stark approach, residual strength is specified with the variable sd_residual_ratio. Residual strength is then computed during initialization as a fraction of the vertical effective stress and is stored in the variable sd_residual_strength. Note that if a non-zero sd_residual_ratio is specified, any existing values for sd_residual_strength will be overwritten.

Key Output Parameters

Some of the key model output parameters for inspecting analysis results are listed below. Contour plots and/or time histories of these variables are typically included in reports.

Property	Description
pp_ratio	Pore pressure ratio: Number between 0 and 1, with 1.0 implying 100% liquefaction. (limited to 0.98)

stress_ratio	Shear stress (sxy) normalized by the initial vertical stress in element. This is the parameter that is tracked to detect shear stress cycles
csr_max	Maximum (peak) stress ratio computed during cycling. Typically an equivalent linear analyses would use this number alone to asses pore pressure and factor of safety against liquefaction

Properties of interest related to the cyclic strength correction factors include:

Property	Description
vertical_stress	Initial static vertical effective stress recorded during model initialization.
static_stress_ratio	Initial shear stress ratio recorded during model initialization.
k_sigma	Computed K_σ correction factor.
k_alpha	Computed K_α correction factor.

Property variables of interest related to cyclic counting are:

Property	Description
csr_zero	Ending CSR for most recent cyclic detected. This can be plotted together with sd_stress_ratio to monitor cycle counting behavior.
csr_raw	Raw, uncorrected stress ratio for most recent cycle detected
csr_corrected	Corrected CSR for most recent cycle detected
n_liquefaction	Number of cycles for 100% liquefaction for more recent cycle detected.
delta_pp_ratio	Pore pressure ratio increment for most recent cycle detected

Using the Model

For the C++ version of the Dames & Moore model, the grid does not have to be configured for groundwater. And even with the grid configured for groundwater, typically groundwater flow is off during shaking.

The model can be operated in three modes, controlled by the property variable dm_mode. In model 0, the default value, the model behaves like the built in Mohr-Coulomb model and does not generate pore pressure. This mode is used for static the static analysis, in which the initial, pre-shaking in situ state is computed. At the end of the static analysis, just before dynamic shaking, the model is run for 1 step with sd_mode = 1 to perform model initialization. During this initialization step, the model performs the following:

1. Records initial vertical effective stress for each element. This serves as the denominator for computing the cyclic stress ratio.
2. Computes static stress ratio α for each element
3. Computes cyclic strength correction factors K_σ and K_α for each element
4. Computes or limit the post-liquefaction residual strength for each element
5. Records the initial shear modulus, used during shaking to compute the effective-stress-dependent shear modulus

After the initialization step, the property variable dm_mode is set to 2 which is pore-pressure generation mode. The dynamic simulation is run with dm_mode = 2.

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